

ATTENUATION TOMOGRAPHY OF NORTHERN CALIFORNIA AND THE YELLOW SEA/KOREAN PENINSULA FROM CODA-SOURCE NORMALIZED AND DIRECT LG AMPLITUDES

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ABSTRACT

Inversions for regional attenuation ($1/Q$) of Lg are performed in two different regions. The path attenuation component of the Lg spectrum is isolated using the coda-source normalization method, which corrects the Lg spectral amplitude for the source using the stable, coda-derived source spectra. Tomographic images of Northern California agree well with one-dimensional (1-D) Lg Q estimated from five different methods. We note that there is some tendency for tomographic smoothing to increase Q relative to targeted 1-D methods. For example, in the San Francisco Bay Area, which contains high attenuation relative to the rest of the region, Q is overestimated by ~30. Coda-source normalized attenuation tomography is also carried out for the Yellow Sea/Korean Peninsula (YSKP), where output parameters (site, source, and path terms) are compared with those from the amplitude tomography method of Phillips et al. (2005), as well as with a new method that ties the source term to the magnitude and distance amplitude corrections (MDAC) formulation (Walter and Taylor, 2001). The source terms show similar scatter between coda-source corrected and MDAC source perturbation methods, whereas the amplitude method has the greatest correlation with estimated true-source magnitude. The coda-source better represents the source spectra compared to the estimated magnitude and could be the cause of the scatter. The similarity in the source terms between the coda-source and MDAC-linked methods shows that the latter method may approximate the effect of the former, and therefore could be useful in regions without coda-derived sources. The site terms from the MDAC-linked method correlate slightly with global Vs30 measurements. While the coda-source and amplitude ratio methods do not correlate with Vs30 measurements, they do correlate with one another, which provides confidence that the two methods are consistent. The path Q^{-1} values are very similar between the coda-source and amplitude ratio methods except for small differences in the Da-xin-an-ling Mountains, in the northern YSKP. However, there is one large difference between the MDAC-linked method and the others in the region near stations TJN and INCN, which point to site-effect as the cause for the difference.

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OBJECTIVES

Understanding of regional attenuation Q^{-1} can help with structure and tectonic interpretation (e.g., Frankel, 1990), and correcting for the effects of attenuation can lead to better discrimination of small nuclear tests (e.g., Baker et al., 2004; Mayeda et al., 2003; Taylor et al., 2002). Present threshold algorithms for event identification rely on Q models that are derived differently, and the models can vary greatly for the same region. In previous work (Ford et al., 2008), we compared 1-D methods to measure Q_{Lg} and attempted to assess the error associated with the results. The assessment showed the possible influence of lateral attenuation, and in order to understand its importance, we perform inversions for 2-D attenuation in the previous study region of Northern California and extend the analysis to the Yellow Sea/Korean Peninsula (YSKP). In the same spirit as the comparison of 1-D methods, we compare three 2-D methods using the YSKP. The comparison is made for the output site, source, and path parameters.

RESEARCH ACCOMPLISHED

Northern California

The Northern California dataset consists of 158 earthquakes recorded at 16 broadband (20 sps) three-component stations of the BDSN between 1992 and 2004 (Figure 1). Using this data, we implement the amplitude tomography method of Phillips et al. (2005), which assumes the L_g spectrum (A_{Lg}) can be represented as

$$\ln(A_{Lg}) = \ln(S(f)) + \ln(P(f)) - \frac{\pi f}{U} \int_s Q^{-1} ds,$$

where U is the phase velocity, and the inversion solves for $S(f)$ and $P(f)$, the source and site terms, respectively, as well as Q^{-1} along the path, s , in a damped least-squares sense. This method will be referred to as Amp. We also employ an altered form of this method where the source term is corrected using the stable, coda-derived source spectra in order to isolate the path attenuation component of the L_g spectrum (Walter et al., 2007). This method will be referred to as CS. Source spectra derived from the coda are calculated via the methodology of Mayeda et al. (2003) and from the northern California study of Mayeda et al. (2005). Figure 2 compares the two methods for

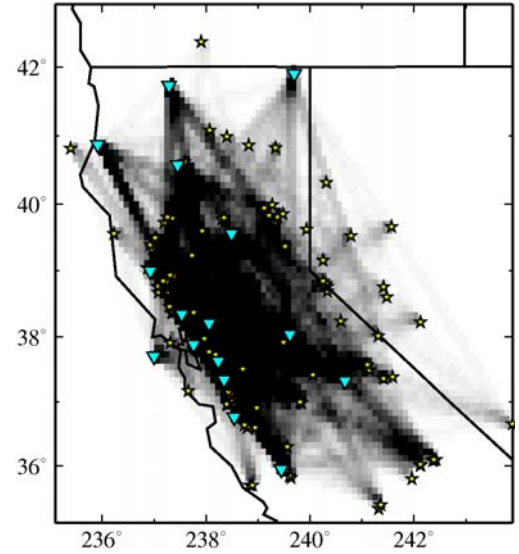


Figure 1. Northern California region with events (yellow stars), stations (blue triangles), and path density.

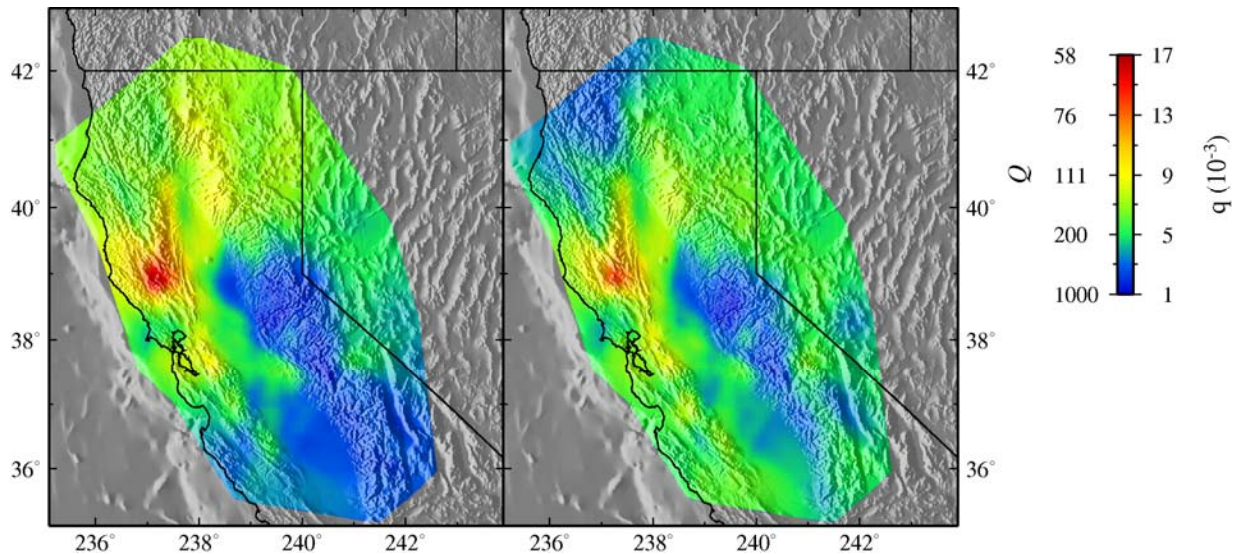


Figure 2. Q_{Lg} at 1 Hz. Left, using the standard amplitude method of Phillips et al. (2005). Right, using the coda-source corrected method.

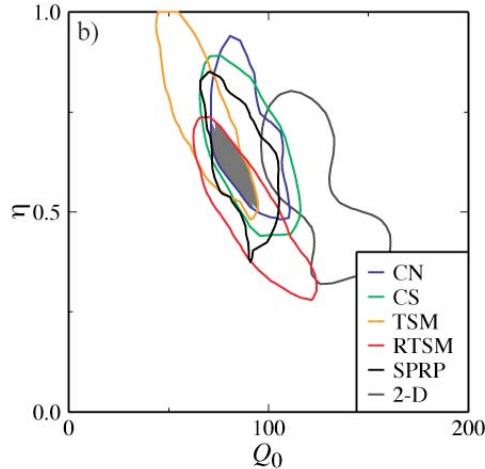


Figure 3. 2-D Q and power-law dependence distribution (grey line) compared with those from various 1-D analyses for the Bay Area. See text for method descriptions.

Northern California. The CS method seems to better constrain path Q when there are few paths, as is the case in the southern section of the Great Valley. The CS-derived tomogram more closely resembles that of Phillips and Stead (2008), which confines the high Q region to the Sierras.

In previous work, we applied the coda normalization (CN), two-station (TS), reverse two-station (RTS), source-pair/receiver-pair (SPRP), and the new coda-source normalization (CS) methods to measure Q of the regional phase, L_g (Q_{Lg}), and its power-law dependence on frequency of the form $Q_0 f^\eta$. The CN method is implemented in the time domain for paths leading to a common station, and it returns a stable Q measurement when the region near a station is homogenous. The CS method uses previously calculated coda-derived source spectra to remove the source term in the frequency domain and is best suited to calculate an effective Q for a given path. The TS and RTS methods are implemented in the frequency domain, and the calculated Q is more stable due to the extraction of the source term. The RTS method produces a power-law Q with less error than the TS method due to its additional extraction of the site terms, though it is more restrictive in its data requirements. The SPRP method is the RTS method with a relaxation of the data requirements and is implemented in the time domain here.

In an attempt to normalize the dataset used for each method, we restricted the data to lie in a small region along the Franciscan block. We implemented all five methods to calculate $Q_0 f^\eta$ in the region. The populations are then smoothed to produce an empirical distribution so that the 95% confidence region can be estimated. We can compare

the 1-D results with those of this 2-D analysis via calculation of the power law parameters for the same region for the CS method by fitting a least-squares line to the Q estimated for each frequency band at the midpoint of the band in the log domain. We extract the power-law parameters at points within the subregion and, as above, we produce an empirical distribution. Figure 3 compares the distributions. The range in η and variance of Q_0 are similar between the 1-D and 2-D results, but the mean of the Q_0 distribution is shifted by about 30. This may be due to some regularization effects. This analysis shows that some of the variability in the 1-D analysis is due to the 2-D structure.

Yellow Sea/Korean Peninsula (YSKP)

The YSKP dataset consists of 146 earthquakes recorded at 6 broadband (20 sps) three-component stations of the glonal seismographic network (GSN) and OHP-Japan (station TJN) networks (Figure 4). Q_{Lg} at 1 Hz is calculated using the CS method and we compare it to previous results to see if this method can produce similar results. The comparison is made in Figure 5 and this study agrees well with previous work, which captures the high attenuation (low Q) in Bohai Bay and the Songliao Basin and low attenuation (high Q) near northern South Korea and in the Changbai Mountains to the east and the Da-xin-an-ling Mountains to the north.

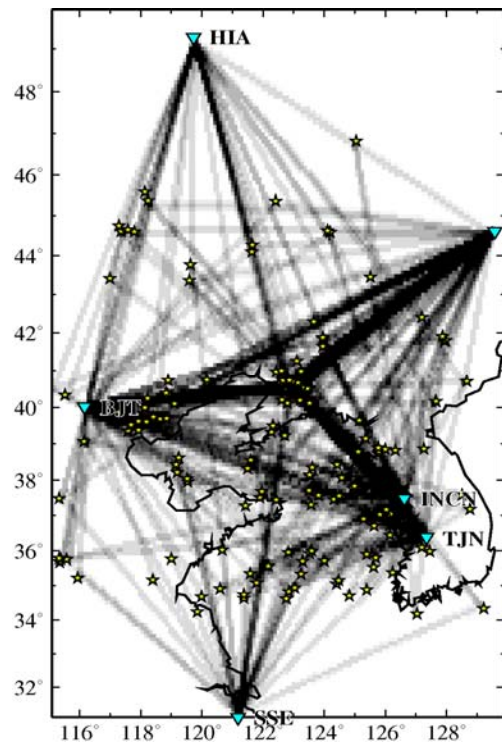


Figure 4. YSKP region with events (yellow stars), stations (blue triangles), and path density.

We implement the same two tomographic methods described above, as well as a new one (Pasyanos et al., 2008, in preparation) that formulates the source term in terms of the MDAC

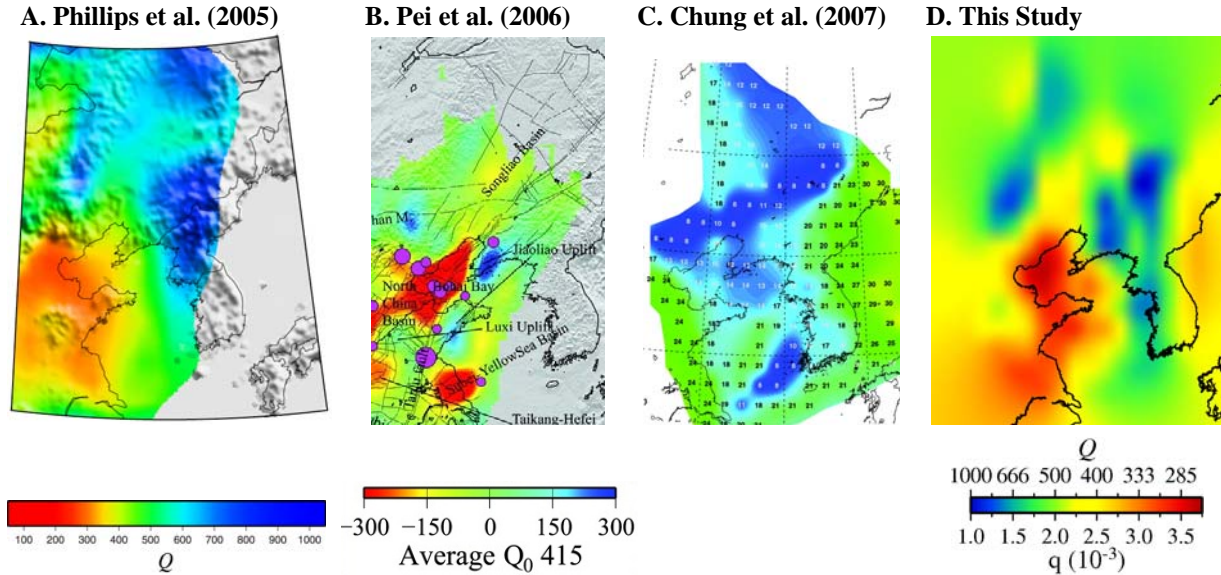


Figure 5. Attenuation tomography comparison for the YSKP. The numbers in Panel C are $1/Q$ (q) $\times 10^4$, blue is low q (attenuation), and green is high q . Panel D shows the coda-source-corrected amplitude tomography results from this study.

(Walter and Taylor, 2001) source. In this way, the output source terms are perturbations to the original source, and this perturbation can be tuned (see Walter et al., these Proceedings). This method will be referred to as the dM method. We can now make a preliminary comparison between the source and site terms (Figure 6) and the path Q (Figure 7) from all three methods.

When the site and source terms are compared with database M_w (first row of Figure 6), the Amp method produces an excellent match, whereas the coda sources used in the CS method and the output M_w s from the dM method produce similar scatter in the source terms. The coda-sources are superior measurements of the source spectra, and the fact that the dM method produces a similar relationship gives high confidence that the source terms from the dM method are reliable. In the dM method, the source terms are expressed directly as a small change to the initial moment making them easier to interpret physically and more easily used for event identification, since they are tied to the MDAC formalism.

When site terms are compared with Vs30 values for each station taken from the topography-derived database of Wald and Allen (2008) (first column of Figure 6), there is no correlation for the Amp and CS methods, but there is a slight correlation for the dM method. However, we are encouraged that the CS and Amp methods produce consistent site terms.

There is little correlation between sediment depth and Q calculated by all three methods (first row and column of Figure 7). Path Q from the CS and Amp methods are highly correlated and differ only along the Da-xin-an-ling Mountains to the north, where the Amp method predicts higher Q than the CS method. This may be a similar effect as what is seen in Northern California for the Great Valley, and therefore the path Q for the CS method is assumed to be more robust, though the difference is slight. Beside the mountain region mentioned earlier, the dM method differs greatly from the other two methods off the coast of Korea (bottom row of Figure 7). This region contains two of the six stations used in the analysis (TJN and INCN), so this difference may be due to a site effect difference. In fact if we look at the comparison between site terms of the CS and dM methods (Figure 6, lower right), one can see that TJN and INCN are the most inconsistent of all the methods.

CONCLUSIONS AND RECOMMENDATIONS

The attenuation tomography methods employed here have difficulty representing extreme attenuation structure, though the lateral variation agrees well with 1-D methods. Initial work with the coda-source corrected amplitude tomography shows that it compares nicely with previous methods and may be able to better constrain Q in regions

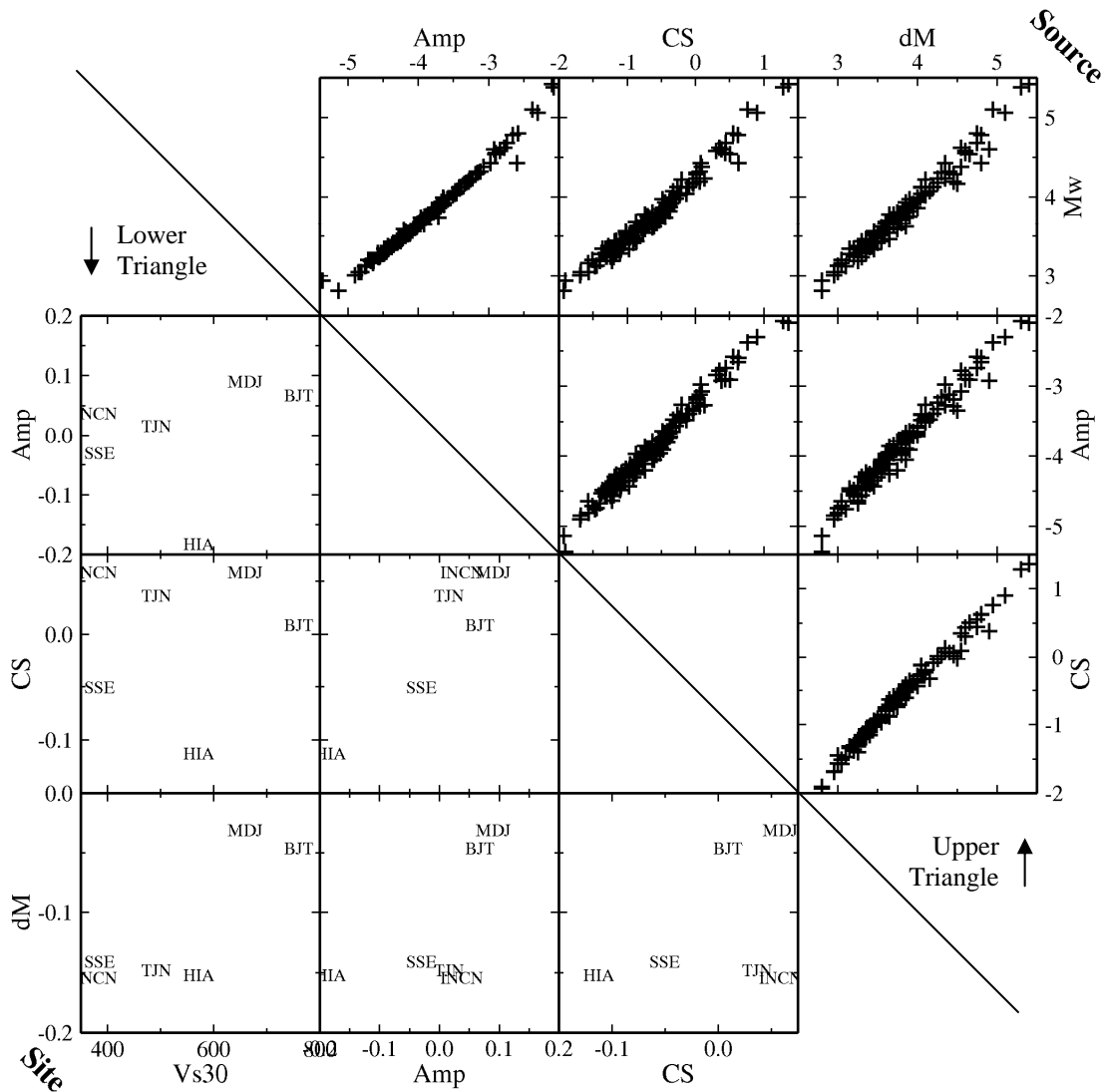


Figure 6. Source and site term comparison for the amplitude tomography method (Amp), coda-source corrected version of that method (CS), and MDAC-formulated method (dM). Source comparison is shown the upper triangle where M_w is from the MDAC database, dM is in units of M_w , CS is in log amplitude of the source spectra, and Amp is in arbitrary log amplitude from the inversion. Note that the dM method can easily be tied to a physical MW. Site comparison is the lower triangle where Vs30 are values from Wald and Allen (2008) and points are given by station names. Values are in arbitrary log units.

with fewer paths. Also, this method can take advantage of larger data sets than the Amp method because the latter is restricted to events recorded at more than one station. A new attenuation tomography method that is tied to the source formalism used in MDAC analysis has the ability to produce output parameters that can be used by MDAC to correct for source and path amplitudes. Preliminary tests of this method show that calculated source terms agree well with the coda-sources and that path Q is similar to standard amplitude tomography.

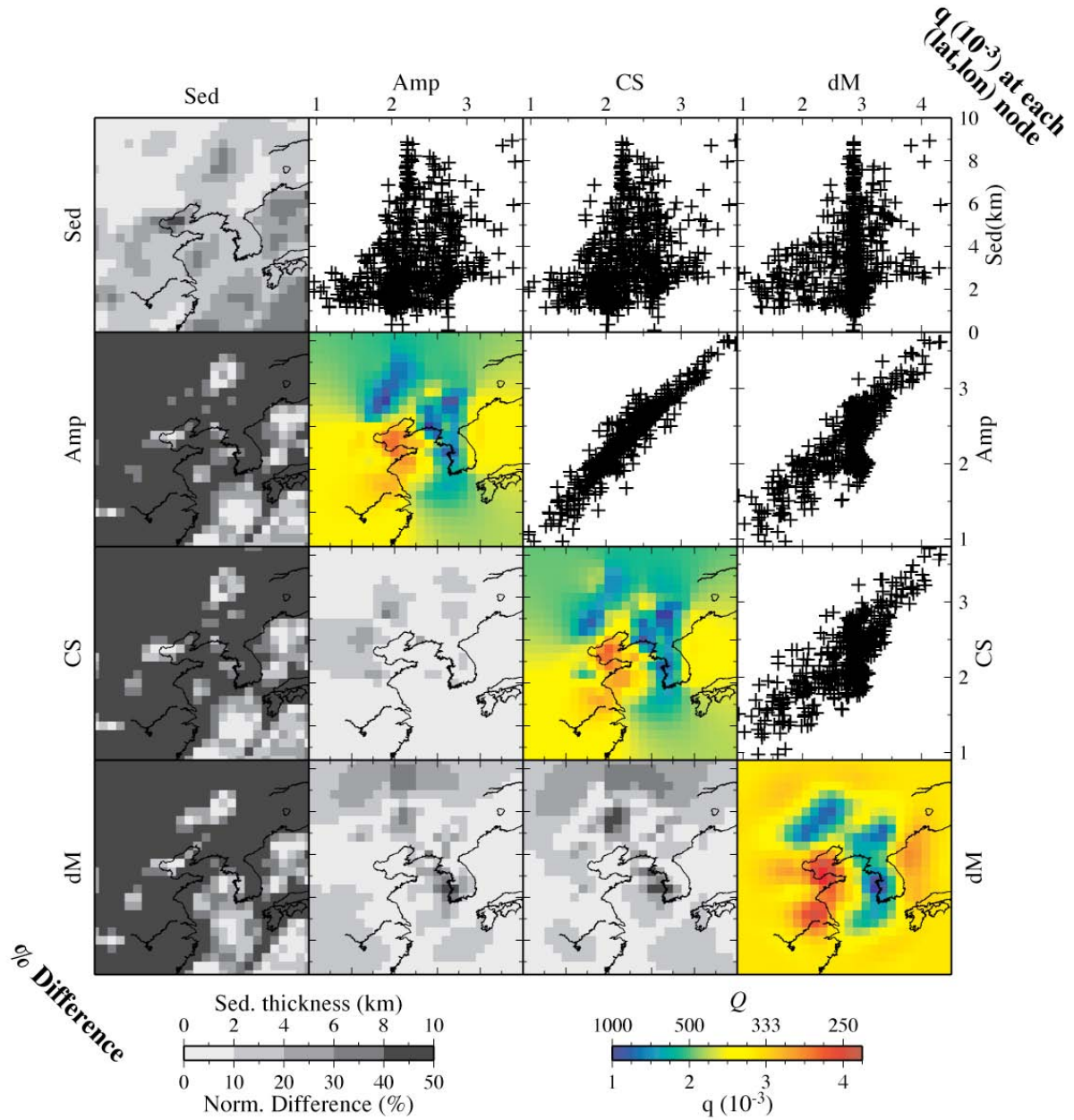


Figure 7. Path Q comparison for the various methods used in this study (see text or Figure 6 for explanation). Diagonal shows attenuation for the YSKP region where Sed is the 1° sediment thickness. Comparison at each node is shown in the upper triangle where values are given in $q (1/Q \times 10^{-3})$ and Sed (sediment thickness) is in km. Spatial comparison in percent difference is shown in the lower triangle.

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REFERENCES

- Baker, G. E., J. Stevens, and H. M. Xu (2004). Lg group velocity: A depth discriminant revisited, *Bull. Seism. Soc. Am.* 94: 722–739.
- Chung, T. W., M. H. Noh, J. K. Kim, Y. K. Park, H. J. Yoo, and J. M. Lees (2007). A study of the regional variation of low-frequency Q_{Lg}^{-1} around the Korean Peninsula, *Bull. Seism. Soc. Am.* 97: 2190–2197.
- Ford, S. R., D. S. Dreger, K. Mayeda, W. R. Walter, L. Malagnini, and W. S. Phillips (2008). Regional attenuation in northern California: A comparison of five 1-D Q methods, *Bull. Seismol. Soc. Am.*, in press.
- Frankel, A. (1990). Attenuation of high-frequency shear waves in the crust: Measurements from New York State, South Africa, and Southern California, *J. Geophys. Res.* 95: 17441–17457.
- Mayeda, K., A. Hofstetter, J. L. O’Boyle, and W. R. Walter (2003). Stable and transportable regional magnitudes based on coda-derived moment-rate spectra, *Bull. Seis. Soc. Am.* 93: 224–239.
- Mayeda, K., L. Malagnini, W. S. Phillips, W. R. Walter, and D. Dreger (2005). 2-D or not 2-D, that is the question: A northern California test, *Geophys. Res. Lett.* 32: L12301.
- Pei, S., J. Zhao, C. A. Rowe, S. Wang, T. M. Hearn, Z. Xu, H. Liu, and Y. Sun (2006). M_L amplitude tomography in North China, *Bull. Seism. Soc. Am.* 96: 1560–1566.
- Phillips, W. S., H. E. Hartse, and J. T. Rutledge (2005). Amplitude ratio tomography for regional phase Q , *Geophys. Res. Lett.* 32: L21301.
- Phillips, W. S. and R. J. Stead (2008). Attenuation of Lg in the western US using the USArray, *Geophys. Res. Lett.* 35: L07307, doi:10.1029/2007GL032926.
- Taylor, S., A. Velasco, H. Hartse, W. S. Philips, W. R. Walter, and A. Rodgers (2002). Amplitude corrections for regional discrimination, *Pure. App. Geophys.* 159: 623–650.
- Wald, D. J. and T. I. Allen (2008). Topographic slope as a proxy for seismic site conditions and amplification, *Bull. Seism. Soc. Am.*, in press, <http://earthquake.usgs.gov/research/hazmaps/interactive/vs30/>
- Walter, W. R., K. Mayeda, L. Malagnini, and L. Scognamiglio (2007). Regional body-wave attenuation using a coda source normalization method: Application to MEDNET records of earthquakes in Italy, *Geophys. Res. Lett.* 34: L10308.
- Walter, W. R. and S. R. Taylor (2001). A revised magnitude and distance amplitude correction (MDAC2) procedure for regional seismic discriminants, Lawrence Livermore National Laboratory report UCRL-ID-146882.